天文研究所
Institute of Astronomy

國立清華大學
NATIONAL TSING HUA UNIVERSITY

Empirical modelling of cosmic ray propagation in magnetized molecular cloud complexes and the impacts on the initial conditions of star-formation

Ellis R Owen

CICA Fellow

ellisowen.org

erowen@gapp.nthu.edu.tw

Institute of Astronomy
National Tsing Hua University

In collaboration with: Shih-Ping Lai (NTHU), Kinwah Wu (UCL), Alvina Y L On (NCTS)

NGC 602; Credit: STScI

Cosmic rays II: The salt of the star-formation recipe – Florence, November 2022

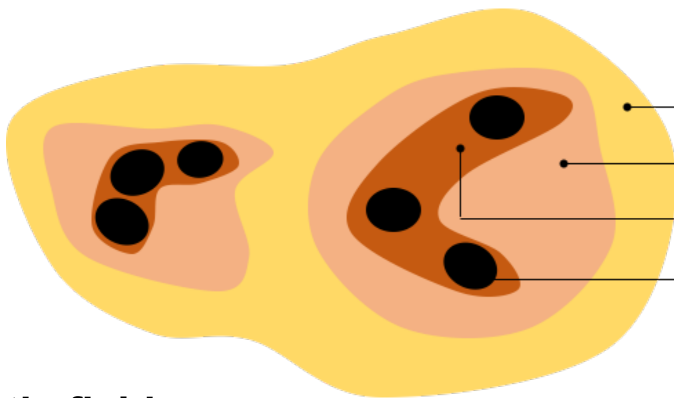
Outline

1. Molecular clouds and CR propagation
2. Empirical determination of diffusion coefficient
3. Application and implications

Referencing paper:
Owen, On, Lai & Wu
ApJ 913, 52 **(2021)**
arXiv: 2103.06542

Hierarchical structure of cloud complexes

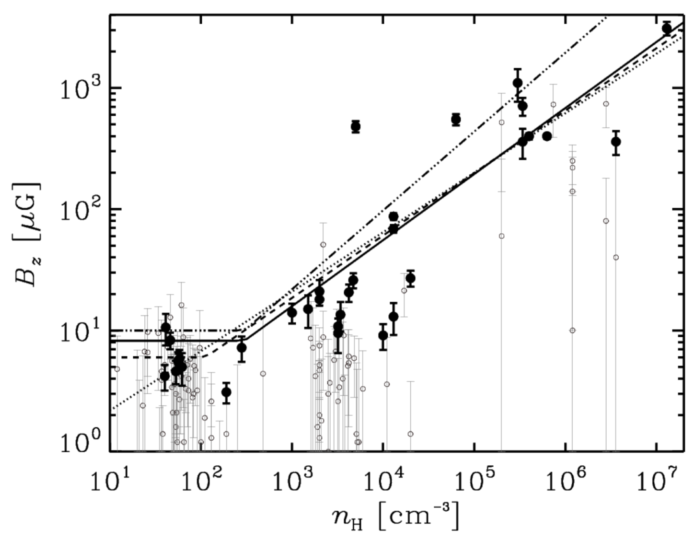
Gas



	Size / pc	Denisty / cm^{-3}
Cloud	~1-10	~ 50-500
Clump	~1	10^3-10^4
Filament	~0.1 (wide)	10^4-10^5
Core	~0.05-0.1	>10^5

(Owen 2022, A&G)

Magnetic field



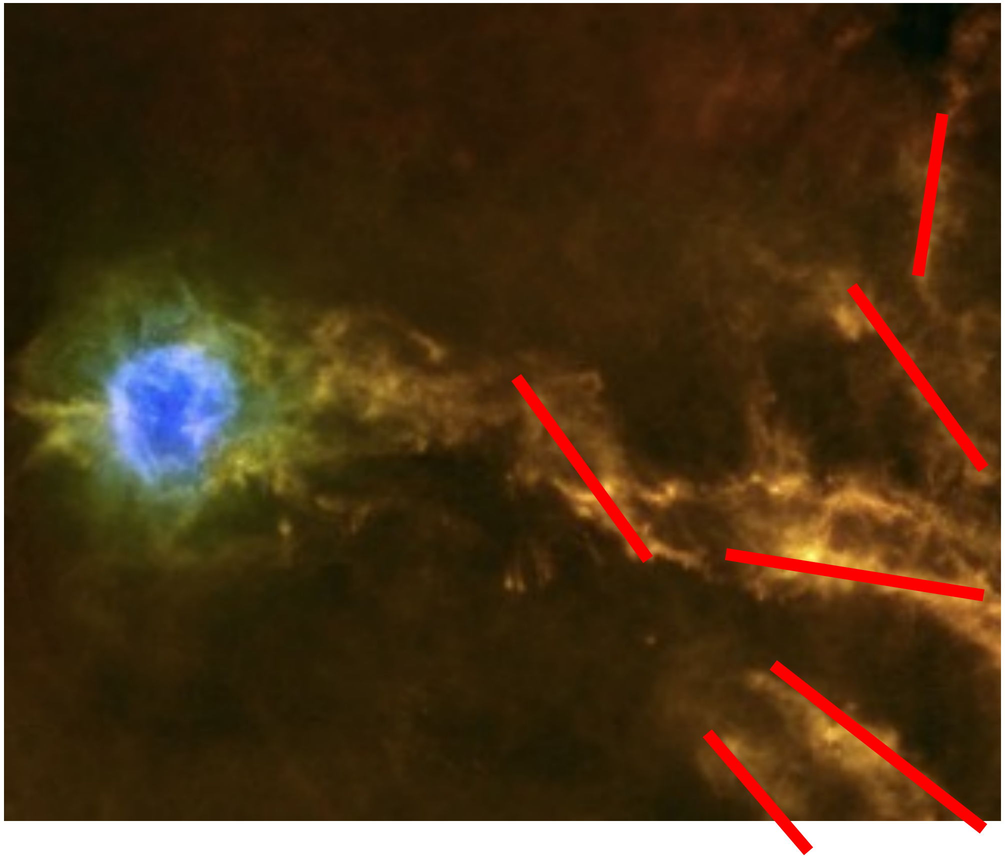
typically B field is stronger in denser regions (with some variation)

(Strong et al. 2014; Crutcher et al. 2010)

Molecular cloud complexes in the Milky Way

Cygnus

Magnetized filamentary structures

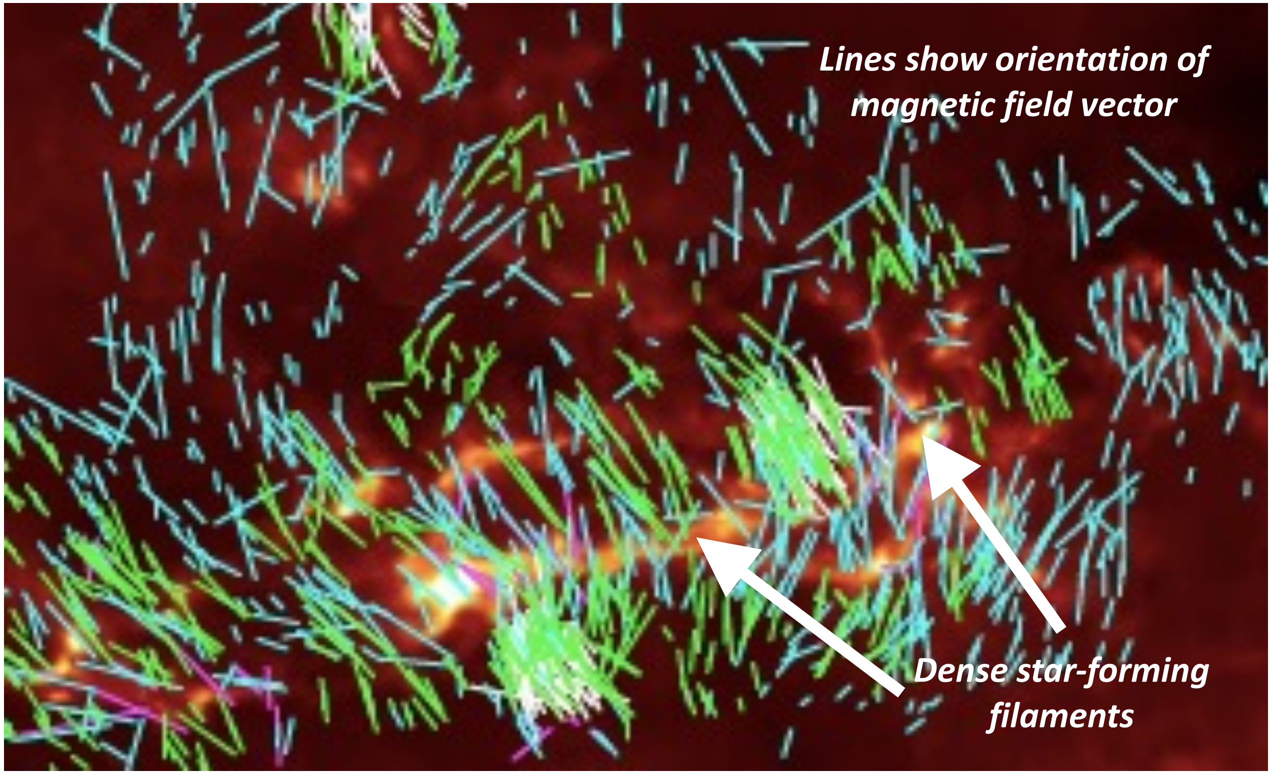


Herschel 250 micro-m (Arzoumanian+ 2011)

Magnetic field structure

polarization from
dust grains aligned
in the magnetic field

IC 5146



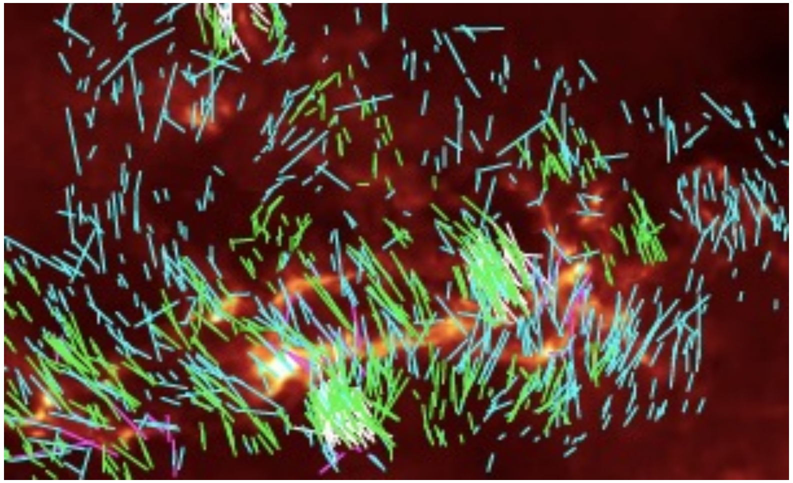
(Wang et al. 2019)

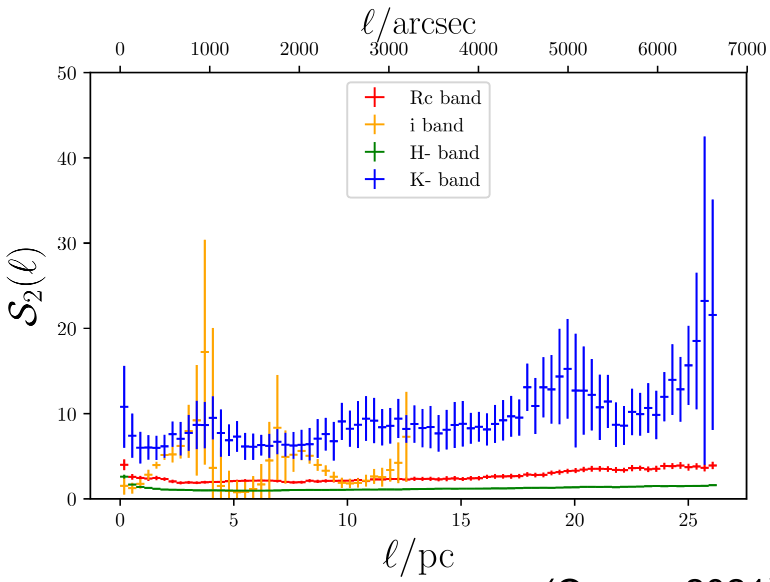
Characterization of field structure

- PA differences as function of separation would trace B field fluctuations

  Structure function (angular dispersion function)

$$\mathcal{S}_d(\ell) = \frac{1}{N_{\mathrm{pair}}} \sum_{i=1}^{N_{\mathrm{pair}}} [\varphi_i(s+\ell) - \varphi_i(s)]^d$$





(Owen+ 2021)

Relation to CR propagation

$$P(k) = \frac{1}{2}\mathcal{F}[\mathcal{S}_2(\ell)]$$

(random component)

$$P(k) \approx P_{\|}(\kappa_{\|})$$

approximation

$$D \approx \frac{2\,c^2}{15\,P_{\mu\mu}}$$

non-vanishing FP coefficient (flow of CRs mainly parallel to large scale B field)

$$P_{\mu\mu} \approx \frac{\mathcal{J}(\lambda_1)}{v_{\mathrm{A}}\,\lambda_1}\left(\frac{\omega_{\mathrm{L}}\,B_0}{B}\right)^2 \mathcal{I}_{\perp}$$

captures self-amplification effect and energy dependencies

$$\mathcal{J}(\lambda_1) = k_{\mathrm{c}}^{-1}\int_0^{\lambda_1 k_{\mathrm{c}}} \mathrm{d}\kappa_{\|}\,\frac{\kappa_{\|}}{k_{\mathrm{c}}\lambda_1}\hat{P}_{\|}(\kappa_{\|}) + k_{\mathrm{c}}^{-1}\int_{\lambda_1 k_{\mathrm{c}}}^{\infty} \mathrm{d}\kappa_{\|}\,\frac{k_{\mathrm{c}}\lambda_1}{\kappa_{\|}}\hat{P}_{\|}(\kappa_{\|})$$

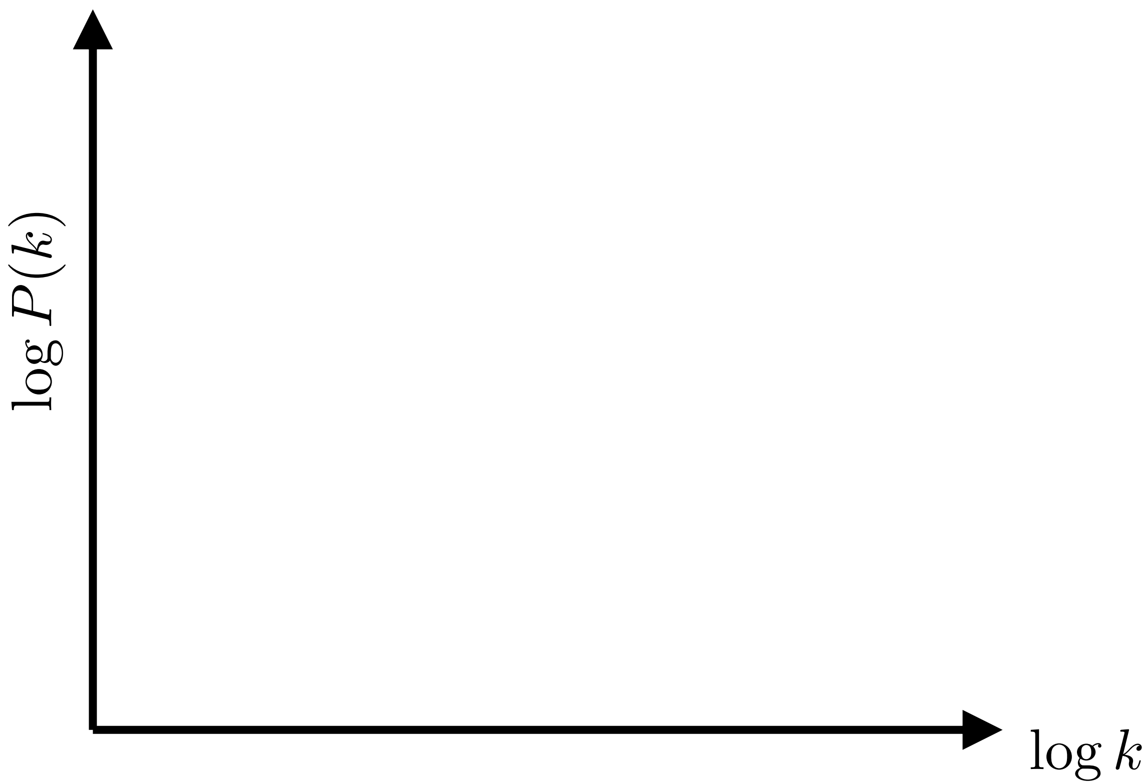
diffusion at E inversely proportional to power in corresponding k

Practical considerations

$$P(k) = \frac{1}{2}\mathcal{F}[\mathcal{S}_2(\ell)]$$

(random component)

$$D \propto \frac{1}{P(k)}$$



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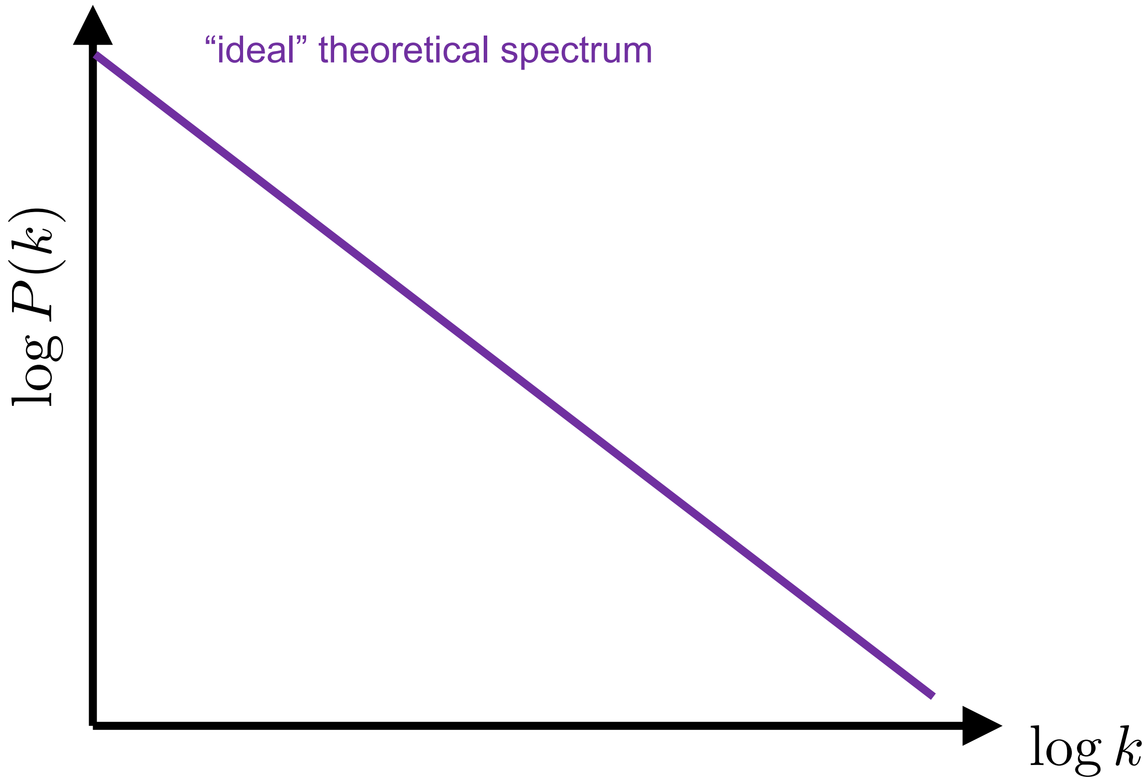

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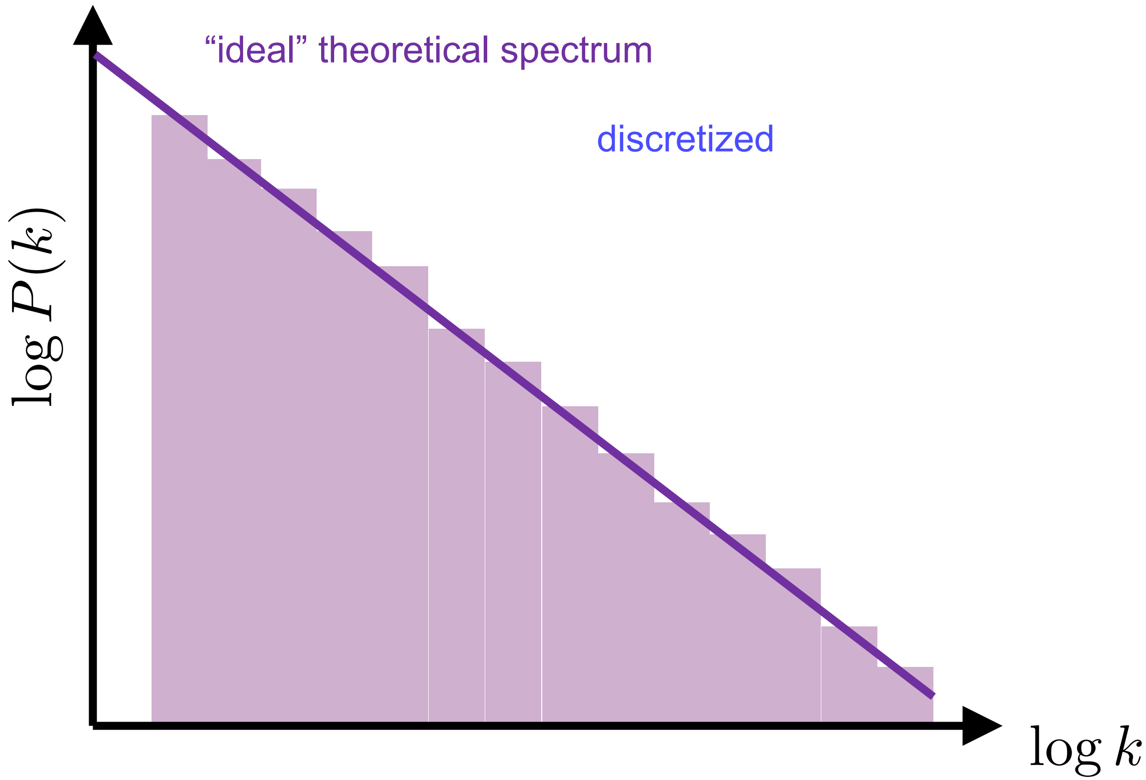

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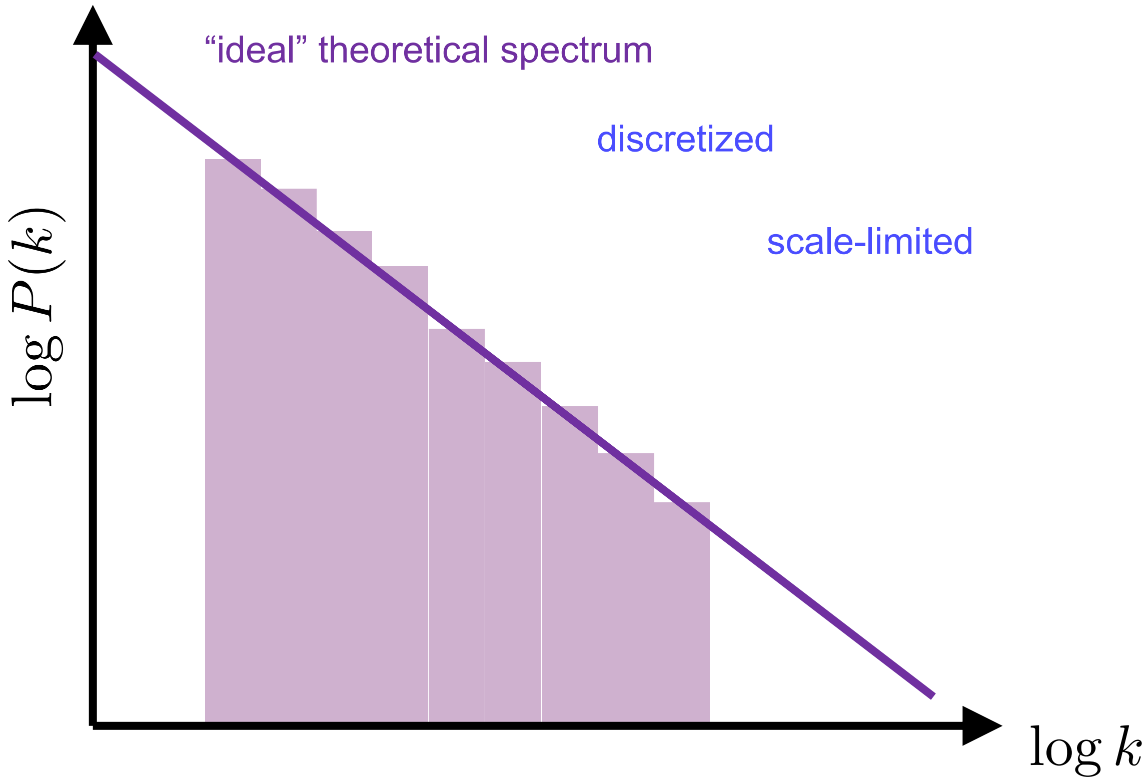

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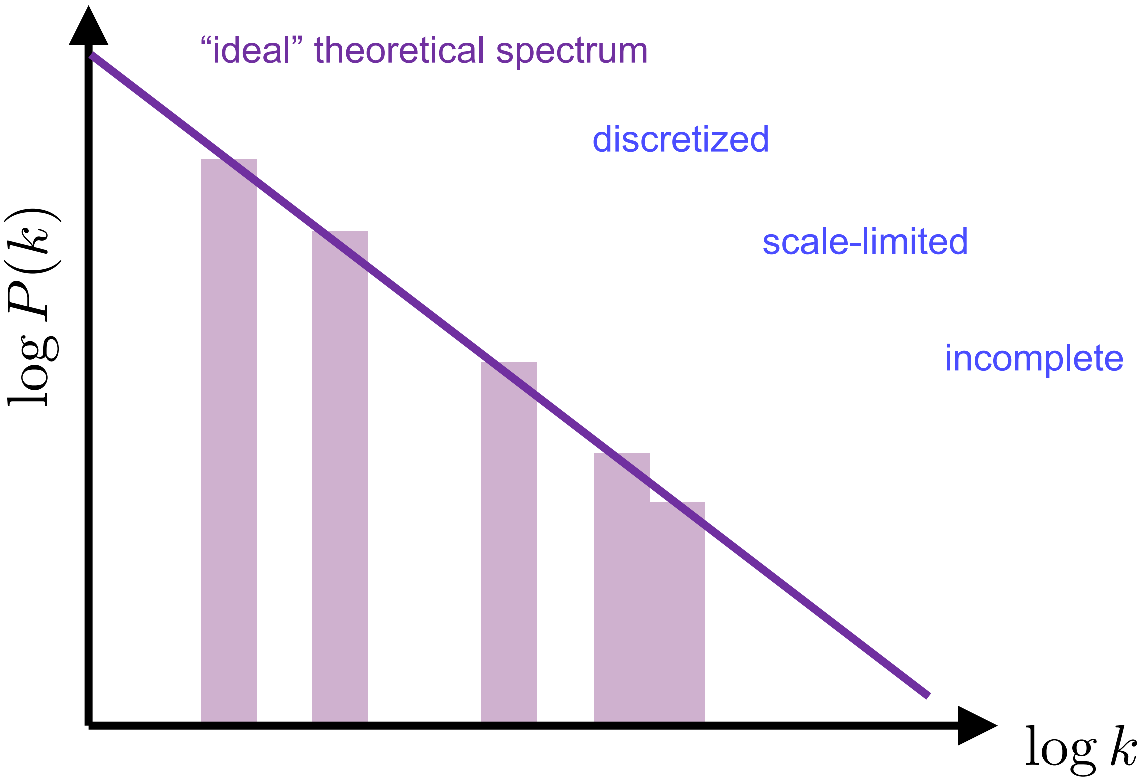

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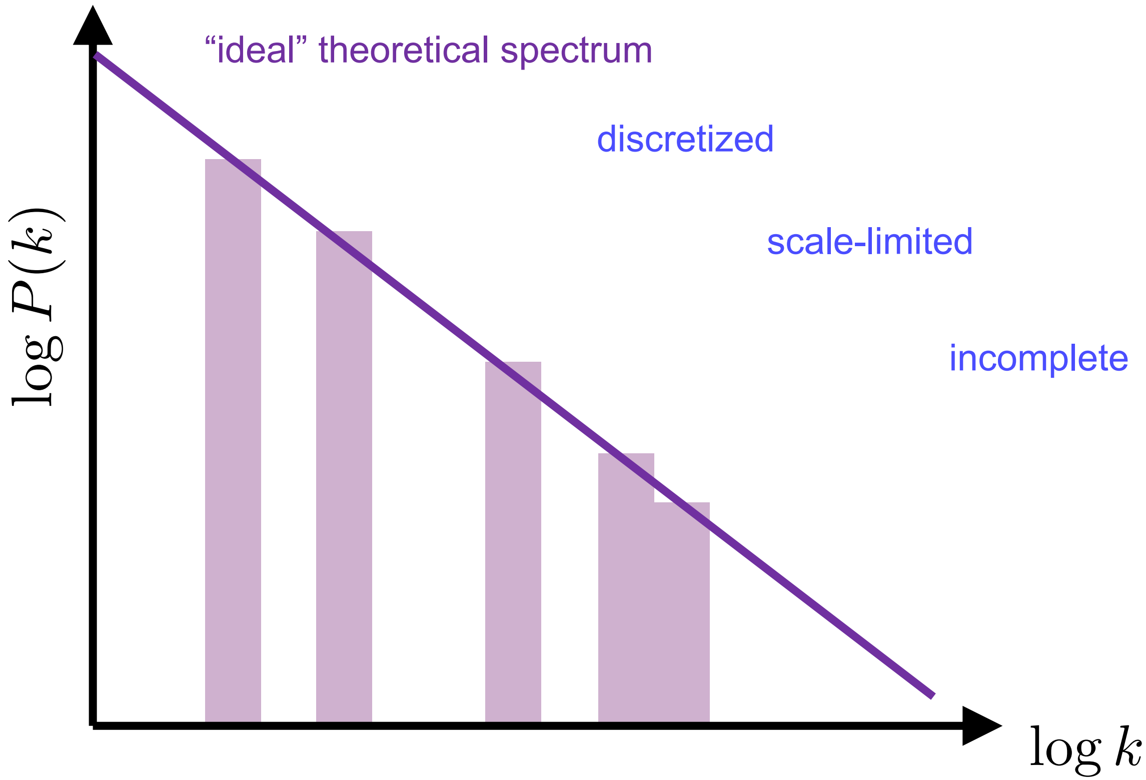


Empirical approach doesn't get full picture (micro-pc scale), **but is still useful**

(1) Identifies the lengthscale over which there is **variation in CR diffusion**

(2) Lower limit to deflection; **upper limit** to **diffusion** (averaged over smaller scales)

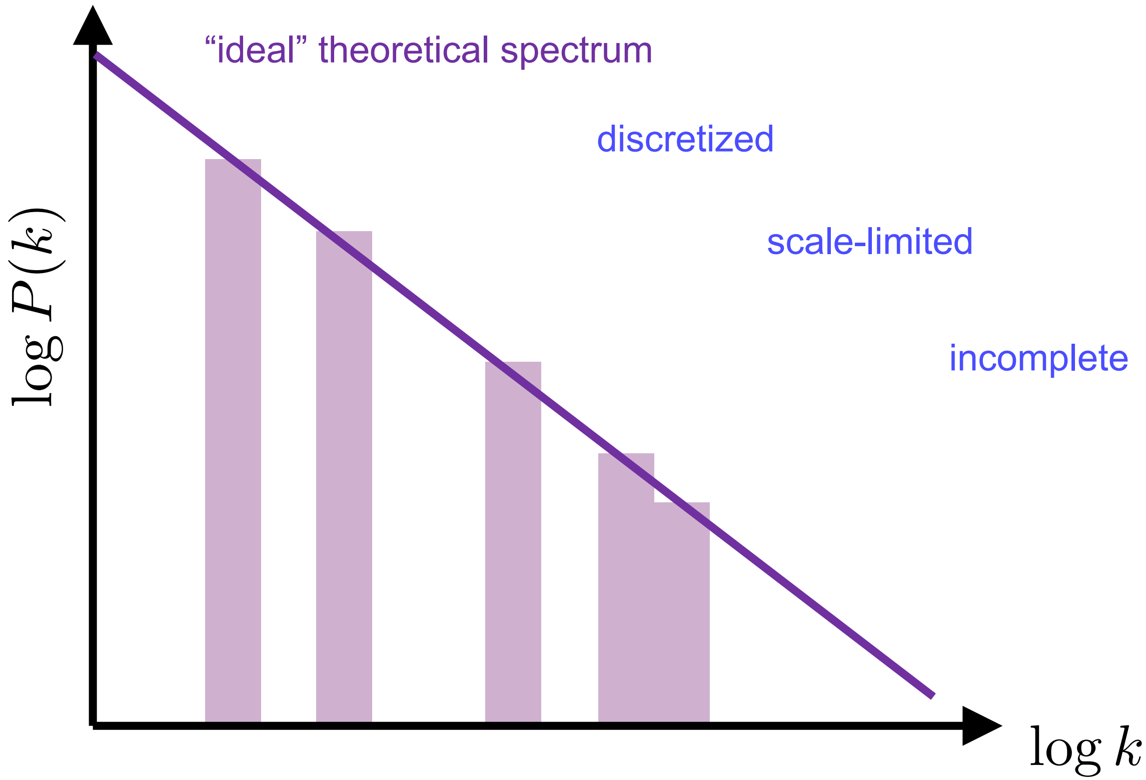
Practical considerations

$$P(k) = \frac{1}{2}\mathcal{F}[\mathcal{S}_2(\ell)]$$

(random component)

$$D \propto \frac{1}{P(k)}$$

Most useful case:
resolve down to diffusion length (~few pc) to capture variation relevant to CR propagation



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Putting it all together…

- Reduce the problem: quickly settles to a steady state

$$\frac{\partial n}{\partial t} = \nabla \cdot [D(E,\mathbf{x})\nabla n]$$ Diffusion

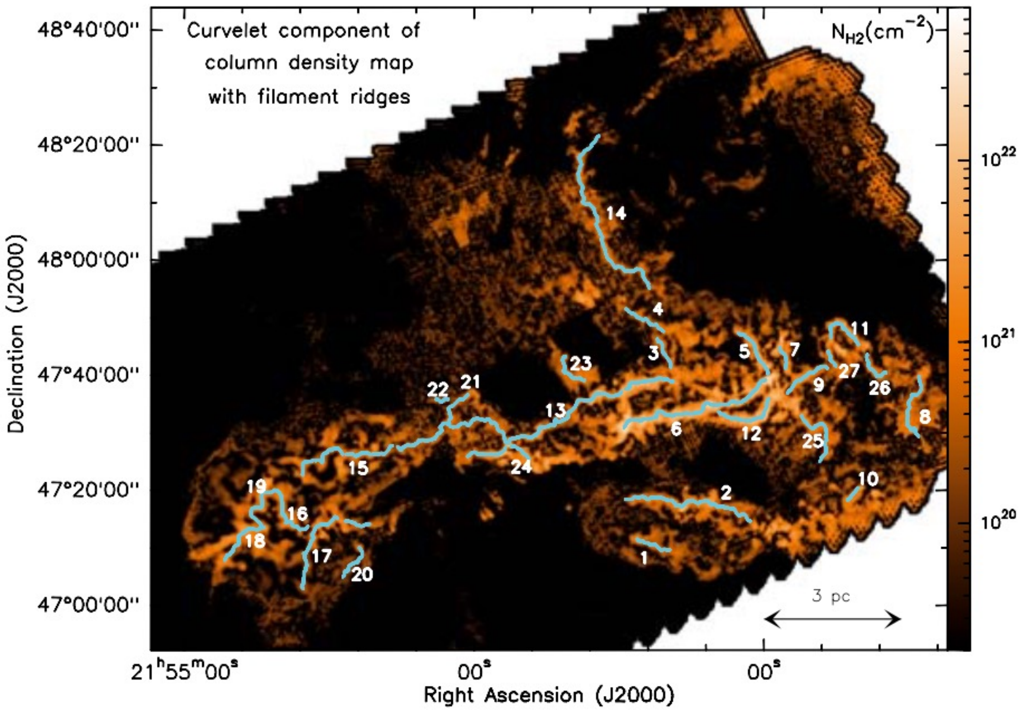
$$+ \frac{\partial}{\partial E}[b(E,r)\,n]$$ Cooling (momentum diffusion)

$$- \nabla \cdot [\mathbf{v}n]$$ Advection

$$+ Q(E,\mathbf{x}) - S(E,\mathbf{x})$$ Source/sink

boundary condition

Application to IC 5146

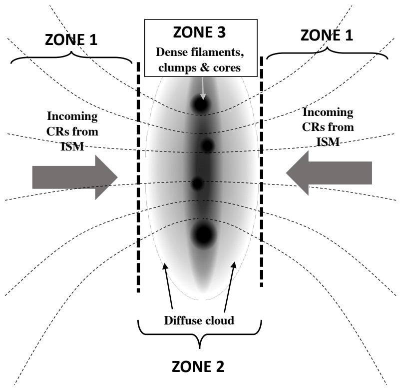


Arzoumanian+ 2011

Application to IC 5146

- Ionization signatures

- These can produce chemical tracers as CR signatures



ID	p	$R_{\rm flat}$/pc	$n_{\rm c}/10^4\ {\rm cm}^{-3}$	$\zeta^{\rm H,min}_{\rm LECRs}/10^{-20}\ {\rm s}^{-1}$	$\zeta^{\rm H,max}_{\rm LECRs}/10^{-15}\ {\rm s}^{-1}$
1	2.1	0.09	0.3	2.1	4.4
2	1.9	0.1	0.7	2.1	4.5
4	1.4	0.04	0.7	2.1	4.5
5	1.5	0.02	7	2.1	4.4
6	1.7	0.07	4	2.1	4.5
7	1.6	0.05	2	2.1	4.5
8	1.5	0.09	0.4	2.1	4.6
9	1.5	0.07	0.8	2.1	5.0

Application to IC 5146

- Heat/ionize molecular clouds; impacts on star-formation

  See also works by Padelis Papadopoulos

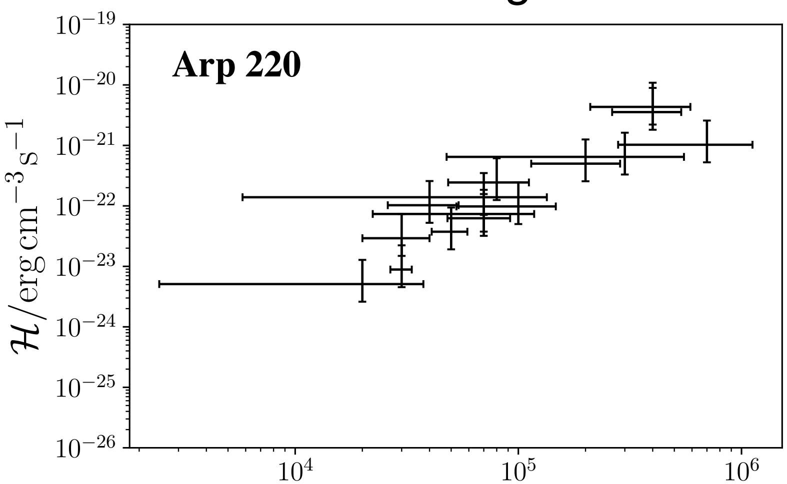
ID	p	R_{flat} / pc	n_c / 10^4 cm^{-3}	$\mathcal{H}$ / 10^{-26} erg cm^{-3} s^{-1}	$T_{eq,CR}$ / K
1	2.1	0.09	0.3	0.59	0.8
2	1.9	0.1	0.7	9.2	1.7
4	1.4	0.04	0.7	4.3	1.3
5	1.5	0.02	7	68	2.5
6	1.7	0.07	4	290	4.0
7	1.6	0.05	2	33	2.2
8	1.5	0.09	0.4	6.8	1.8
9	1.5	0.07	0.8	16	2.0
10	2.1	0.1	0.5	2.5	1.2
11	1.9	0.07	1	6.5	1.5
12	1.5	0.05	4	240	3.7
13	1.6	0.04	3	4.3	2.3
20	1.5	0.05	0.2	0.34	0.7

Some extrapolation…

See also ***Owen, On, Lai & Wu PoS ICRC 053 (2021)*** *arXiv: 2107.11734*

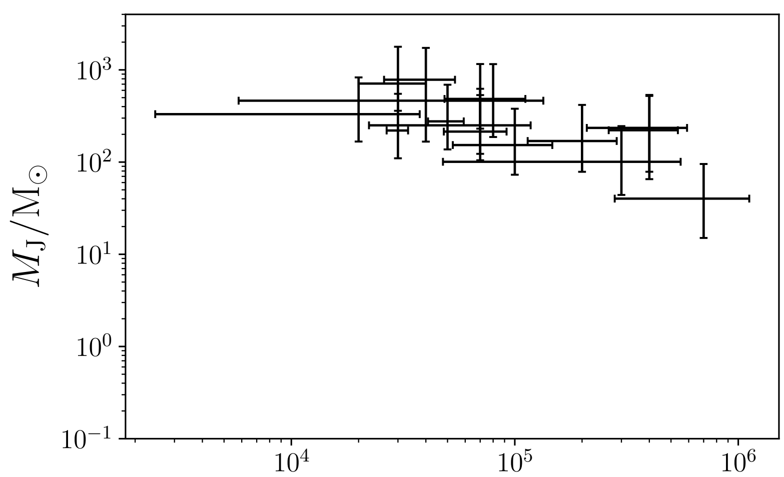
- Higher CR energy density in star-forming galaxies
- Stronger; affects stability; Temperature → Jeans' mass
- **What does this mean for star-formation?**

Heating



Filament density/cm^{-3}

Jeans' Mass



Filament density/cm^{-3}

Summary

- Empirical assesment of CR propagation through star-forming regions can be achieved with new and upcoming dust polarization data
- Although limited by quality of data, still useful and meaningful (especially if resolved down to diffusion scales)
- Allows new view of the variation of CR effects through cloud complexes
- An empirical view of the 'feedback' effect of CRs on the 'sub-grid' scale

For details see full paper:
Owen, On, Lai & Wu
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arXiv: 2103.06542